Chapter 3

From the Middle Ages to Heliocentrism

3.1 Preamble

The Roman empire produced no scientific progress in the area of cosmology, and the Church tainted it during most of the Middle Ages. Europe forgot most of the discoveries of the Greeks until they were reintroduced by Arab astronomers in the XII-th century through the Crusades and other less distressing contacts. The Renaissance brought a breath of fresh air to this situation, and allowed for the heretofore untouchable dogmas to be re-examined, yet, even in this progressive climate, the influence of the Church was still enormous and this hampered progress.

In the XVI-th century the Copernican view of the solar system saw the light. In this same era the quality of astronomical observations improved significantly and Kepler used these data to determine his famous three laws describing the motion of the planets. These discoveries laid the foundation for the enormous progress to be achieved by Galileo and then Newton.

3.2 The Middle Ages.

The development of new scientific theories came almost to a stop during the centuries covering the Roman Empire and the Middle Ages. During this long period there was a gradual emergence of irrational theories that threatened to engulf the whole of science: astrology challenged astronomy, magic insinuated itself into medicine and alchemy infiltrated natural science. The

beginning of the Christian era, when Oriental mysticism became the rage in Greece and Rome, witnessed the appearance of exotic sects such as the Gnostics and the Hermetics who propagated distorted and over-simplified cosmologies ostensibly given to them by God [1].

During the Middle Ages European mental efforts were directed towards non-scientific pursuits. This attitude was perpetuated by the absence of libraries and the scarcity of books (both a consequence of the economic depression suffered by Europe at that time), and by the constraints imposed by the Church which forbade various ares of investigations as they were felt to be against the teachings of the Bible.

These problems did not permeate the whole world, however, and, in fact, Arab science flourished during this time devising the now-common Arab numerals, increasingly accurate time-keeping devices and astronomical instruments, and providing corrections to Ptolemy's observations. Later, through the close contacts generated by the Crusades, Arab knowledge was carried to Europe.

The scientific climate in Europe improved by the XIII century with the creation of the first universities. It was during this last part of the Middle Ages that the 3 dimensional nature of space was determined and the concept of force was made precise. The experimental basis of scientific inquiry was recognized as well as the need for internal logical consistency. With these developments the field was ready for the scientific developments of the Renaissance.

Through all these medieval tribulations Ptolemy's magnum opus, the *Alamgest*, together with Aristotle's *On The Heavens* survived as *the* cosmological treatises. Their influence became widespread after translations into Latin became readily available (at least at the universities). There was much discussion on the reconciliation of Aristotle's view of the world and the descriptions found in the Bible. Issues such as whether the universe is infinite and whether God can create an infinite object were the subject of heated discussions.

Sometimes the conclusions reached by the philosophers were not satisfactory to the theologians of the era and, in fact, in 1277 the bishop of Paris collected a list of 219 propositions connected with Aristotle's doctrine which no-one could teach, discuss or consider in any light under penalty of excommunication. For example,

- Aristotle argued against the possibility of there being other worlds, that is, copies of his set of spheres which are supposed to describe our

[1] From, *A History of Science* by H. Smith Williams.

world; these arguments can be interpreted as stating that God does not have the power to create such other worlds, an idea unacceptable to the Church.

- Aristotle assumed matter to be eternal and this contradicted the creation of matter, and in fact, of the whole universe by the will of God.
- Aristotelian advocates believed in the eternal pre-ordained motion of heavenly bodies which *nothing* could alter, this again implied limits on the powers of God.

In my opinion there is an interesting issue connected with the conflict between the Bible and Aristotle. It was Aristotle's belief that there are rules which objects are, by their very nature, forced to obey without the need for divine intervention. It is this idea that is prevalent in science today: there are natural laws that determine the behavior of inanimate objects without the intervention of higher authority. It is always possible to argue who or what determines these natural laws, whether there is some underlying will behind all of this. But that lies beyond the reach of science (at least in its present form), not because the question is of no interest, but because it cannot be probed using the reliable framework provided by the scientific method (Sect. **??**).

It was Aristotle's belief that there are natural laws that determine the behavior of inanimate objects without the intervention of higher authority

The problems with the theory of the universe perfected by Ptolemy were not apparent due to deficiencies in the instruments of the time. First was the problem of keeping time accurately: there were no precise clocks (a problem solved only when Galileo discovered the pendulum clock); a state of the art time-keeping mechanism of that time, the water-clock, is illustrated in Fig. 3.1; such mechanisms were not significant better than the water clocks used in Egypt starting form 1600 B.C. Secondly there was a notational problem: large numbers were very cumbersome to write since only Roman numerals were known (this notation has no notion of zero and of positional value; see Sect. **??** for a comparison between modern and Roman numerals).

These problems were recognized and (eventually) solved. The Arabic number system was slowly accepted in the Western world after its first introduction around 1100 A.D. during the Crusades. The discoveries of the other Greek scientists (not belonging to the Ptolemaic school) were also introduced in the West during this period in the same way. The first mechanical clocks waere developed in Europe in the XIII-th century. They worked using pulleys and weights but were still very inaccurate: the best ones were able only to give the nearest hour!

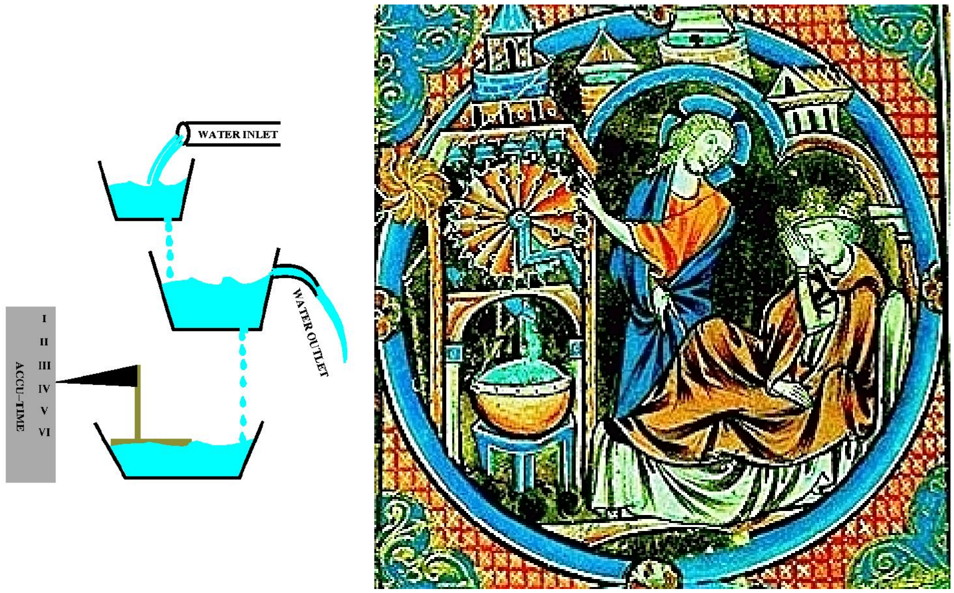


Figure 3.1: Illustrations of a water clock (left) and its use (right).

Despite the bad connotation the Middle Ages have, not all aspects of life during that time were horrible. In fact the basic ideas behind the universe in this time were very comforting to Jews, Christians and Muslims. These ideas provided a stable framework where most people had a (reasonably) clear view of their place in society, their duties and expectations.

The universe had the Earth at its center with all heavenly bodies circling it. Beyond the last sphere (that of the fixed stars) lay paradise, hell was in the bowels of the Earth (a sort of "under-Earth"), and purgatory was in the regions between Earth and the Moon (Fig. 3.2). One of the main architects of this vision was Thomas Aquinas whose view was adopted by Dante in his Divine Comedy.

The Middle Ages provided the gestation period during which the necessary conditions for the Renaissance were created. This is witnessed by the writings of various visionaries, with Roger Bacon as the best example. Bacon believed that Nature can be described using mathematics and required that all accepted theories be based on experimental evidence, not merely as conclusions drawn from ancient treatises (which themselves have not been tested). Many of these ideas were, of course, of Greek ancestry.

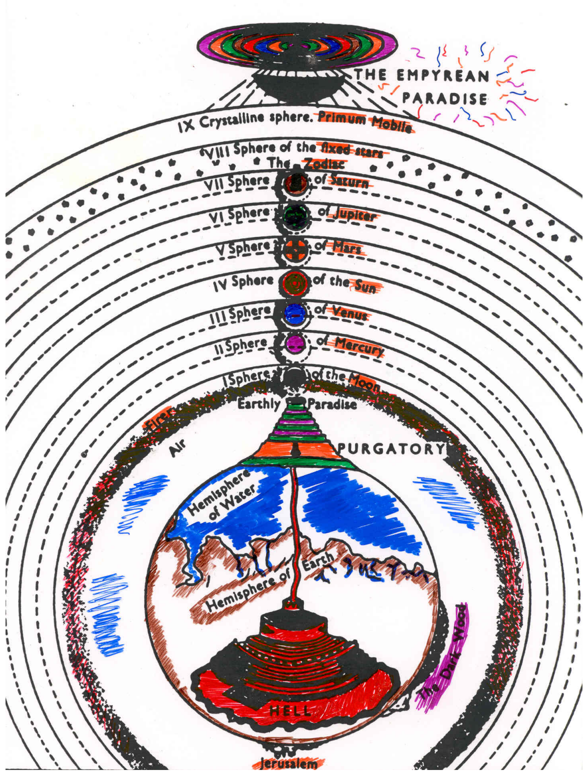


Figure 3.2: Illustration of a typical Medieval cosmological model.

Roger Bacon (1220–1292). He is remembered for his work in mathematics, and as a early advocate of the scientific method. He was a student at the university in Paris and later at Oxford in England. He became a Franciscan friar during the 1250s. His works include writings in mathematics, alchemy, and optics. He is known to have authored *Compendium of the Study of Philosophy* (1272) and *Compendium of the Study of Theology* (1292). During his life time he experimented with ideas about the development of gunpowder, flying machines, motorized vehicles, and telescopes.

Also worth of mentioning is William of Ockham, who parted from Plato's

claim that ideas are *the* true and eternal reality (we only see imperfect shadows cast by these ideas, and this taints our perception of Nature). Ockham argued in his famous “razor” statement that this is an unnecessary complication in the description of Nature: *pluralitas non est ponenda sine neccesitate*, entities must not be needlessly multiplied, which was discussed extensively in Sect. **??**.

Entities must not be needlessly multiplied

William of Ockham (1285-1349). Born in Ockham – near Ripley, Surrey – England, died in Munich, Bavaria – now Germany. Ockham's early Franciscan education concentrated on logic. He studied theology at Oxford and between 1317 and 1319 he lectured on the Sentences , the standard theology text used in universities up to the 1600's. His opinions aroused strong opposition and he left Oxford without his Master's Degree. He continued studying mathematical logic and made important contributions to it. He considered a three valued logic where propositions can take one of three truth values. This became important for mathematics in the 20th Century but it is remarkable that it was first studied by Ockham 600 years earlier. Ockham went to France and was denounced by the Pope. He was excommunicated and in 1328 he fled seeking the protection of Louis IV in Bavaria (Louis had also been excommunicated). He continued to attack papal power always employing logical reasoning in his arguments until his death.

Yet the great majority of intellectuals accepted Ptolemy's model of the world. But, was this acceptance based on a belief that this was an accurate description of nature, or just on the fact that there no superior models to replace Ptolemy's? Some astronomers were of the second opinion, for example, the Arab astronomer Averroes declared (in his commentary on Aristotle's works) *“we find nothing in the mathematical sciences that would lead us to believe that eccentrics and epicycles exist”* and *“actually in our time astronomy is nonexistent; what we have is something that fits calculation but does not agree with what is”*. Similarly, Bacon believed that epicycles were a convenient mathematical description of the universe, but had no physical reality. Another notable exception to the general acceptance of Ptolemy's model was, perhaps not surprisingly, Leonardo da Vinci who at the dawn of the Renaissance concluded that the Earth moves (which implies that the Sun does not).

Leonardo da Vinci (1452-1519). Born in Vinci – near Empolia, Italy – died in Cloux – Amboise, France. Leonardo da Vinci had many talents in addition to his painting. He worked in mechanics but geometry was his main love. Received the usual elementary education of reading, writing and arithmetic at his father's house. From 1467 to 1477 he was an apprentice learning painting, sculpture and acquiring technical and mechanical skills; accepted into the painters' guild in Florence in 1472. From that time he worked for himself in Florence as a painter. During this time he sketched pumps, military weapons and other machines.

Was in the service of the Duke of Milan (1482–1499) as a painter and engineer. Completed six paintings and advised on architecture, fortifications and military matters. Also considered a hydraulic and mechanical engineer. During this time he became interested in geometry to the point of being neglectful of his paintings.

Leonardo studied Euclid and Pacioli's Suma and began his own geometry research, sometimes giving mechanical solutions, for example gave several such methods of squaring the circle. Wrote a book on the elementary theory of mechanics which appeared in Milan around 1498.

Leonardo certainly realized the possibility of constructing a telescope (as verified by sections of Codex Atlanticus and Codex Arundul). He understood the fact that the Moon shone with reflected light from the Sun. He believed the Moon to be similar to the Earth with seas and areas of solid ground.

In 1499 the French armies entered Milan and the Duke was defeated. Leonardo then left Milan, traveled to Mantua, Venice and finally Florence. Although he was under constant pressure to paint, but kept his mathematical studies; for a time was employed by Cesare Borgia as a senior military architect and general engineer.

By 1503 he was back in Florence advising on the project to divert the River Arno behind Pisa to help with the siege then suffered by the city. He then produced plans for a canal to allow Florence access to the sea (neither was carried out).

In 1506 Leonardo returned for a second period in Milan. again his scientific work took precedence over his painting and he was involved in hydrodynamics, anatomy, mechanics, mathematics and optics.

In 1513 the French were removed from Milan and Leonardo moved again, this time to Rome. Appears to have led there a lonely life more devoted to mathematical studies and technical experiments in his studio than to painting. After three years of unhappiness Leonardo accepted an invitation from King Francis I to enter his service in France. The French King gave Leonardo the title of first painter, architect, and mechanic of the King but seems to have left him to do as he pleased. This means that Leonardo did no painting except to finish off some works he had with him, St. John the Baptist, Mona Lisa and the Virgin and Child with St Anne. Leonardo spent most of his time arranging and editing his scientific studies. He died in 1519.

Finally I'd like to mention a peculiar alternative to the Aristotle+Ptolemy view of the world: the "Dairy cosmology", due to an Italian miller called Domenico Scandella (1532-1599/1600?), called Menoccio. Scandella believed that God and the angels were spontaneously generated by nature from the original chaos *"just as worms are produced from a cheese"*. The chaos was made of the four elements air, water, earth and fire, and out of them a mass formed *"just as cheese forms from milk"*. Within this mass of cheese, worms appeared, and *"the most holy majesty declared that these should be God and the angels."* Menoccio was tried by the Inquisition, found guilty and executed in 1599 or 1600.

3.3 The Copernican Revolution

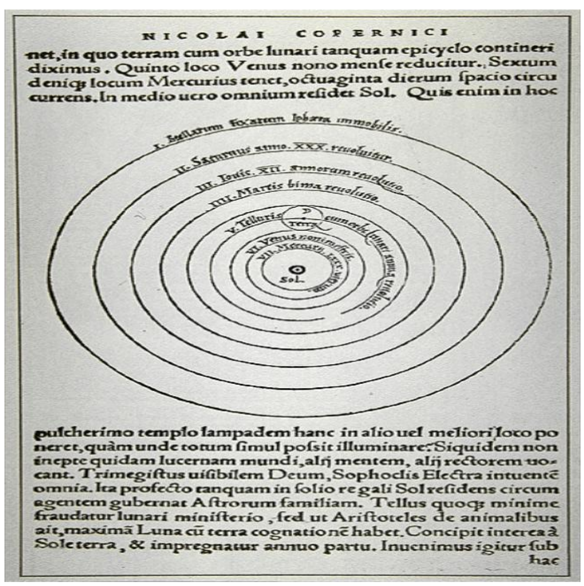
The 16th century finally saw what came to be a watershed in the development of Cosmology. In 1543 Nicolas Copernicus published his treatise *De Revolutionibus Orbium Coelestium* (The Revolution of Celestial Spheres) where a new view of the world is presented: the heliocentric model.

It is hard to underestimate the importance of this work: it challenged the age long views of the way the universe worked and the preponderance of the Earth and, by extension, of human beings. The realization that we, our planet, and indeed our solar system (and even our galaxy) are quite common in the heavens and reproduced by myriads of planetary systems provided a sobering (though unsettling) view of the universe. All the reassurances of the cosmology of the Middle Ages were gone, and a new view of the world, less secure and comfortable, came into being. Despite these "problems" and the many critics the model attracted, the system was soon accepted by the best minds of the time such as Galileo

Copenicus' model, a rediscovery of the one proposed by Aristarchus centuries before (see Sect. **??**), explained the observed motions of the planets (eg. the peculiar motions of Mars; see Fig. **??**) more simply than Ptolemy's by assuming a central sun around which all planets rotated, with the slower planets having orbits farther from the sun. Superimposed on this motion, the planets rotate around their axes. Note that Copernicus was not completely divorced from the old Aristotelian views: the planets are assumed to move in circles around the sun (Fig. 3.3).

Copernicus' model consisted of a central sun around which all planets rotated, with the slower planets having orbits farther from the sun

Nicholas Copernicus (Feb 19 1473 - May 24 1543). Born Torun, Poland, died Frauenburg, Poland. Copernicus studied first at the University of Krakow which was famous for mathematics, philosophy, and astronomy. Copernicus then studied liberal arts at Bologna from 1496 to 1501, medicine at Padua, and law at the University of Ferrara. He graduated in 1503 with a doctorate in canon law. He then took up duties at the cathedral in Frauenberg. during this period Copernicus performed his ecclesiastical duties, practiced medicine, wrote a treatise on monetary reform, and became interested in astronomy. In May 1514 Copernicus circulated in manuscript *Commentariolus*, the first outline of his heliocentric model; a complete description of which was provided in *De Revolutionibus Orbium Coelestium* in 1543. Copernicus suffered a stroke in 1542 and was bedridden by the time his magnum opus was published, legend has it that he saw the first copies (with an unauthorized preface by Osiander which tried to placate the Church's criticisms) the day he died.



NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono menſe reducitur., Sextum deniq; locum Mercurius tenet, octuaginta dierum ſpacio circu currens. In medio uero omnium reſidet Sol. Quis enim in hoc

pulcherimo templo lampadem hanc in alio uel meliori loco po neret, quàm unde totum ſimul poſsit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uo-cant. Trimegiſtus uiſibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in ſolio regali Sol reſidens circum agentem gubernat Aſtrorum familiam. Tellus quoq; minime fraudatur lunari miniſterio, ſed ut Ariſtoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur ſub

hac

Figure 3.3: The page in Copernicus' book *De Revolutionibus Orbium Coelestium* outlining the heliocentric model.

It must be noted that Copernicus not only put forth the heliocentric idea, but also calculated various effects that his model predicted (thus following

the steps outlined in Sect. ??). The presentation of the results was made to follow Ptolemy's *Almagest* step by step, chapter by chapter. Copernicus' results were quite as good as Ptolemy's and his model was simpler; but its predictions were not superior (since the planets do not actually move in circles but follow another – though closely related – curve, the ellipse); in order to achieve the same accuracy as Ptolemy, Copernicus also used epicycles, but now in the motion of the planets around the Sun. The traditional criticisms to the heliocentric model he answered thusly,

- To the objection that a moving Earth would experience an enormous centrifugal force which would tear it to pieces, Copernicus answered that the same would be true of, say, Mars in the Ptolemaic system, and worse for Saturn since the velocity is much larger.

- To the question of how can one explain that things fall downwards without using the Aristotelian idea that all things move towards the center, Copernicus stated that that gravity is just the tendency of things to the place from which they have been separated; hence a rock on Earth falls towards the Earth, but one near the Moon would fall there. Thus he flatly contradicted one of the basic claims of Aristotle regarding motion.

- To the objection that any object thrown upward would be "left behind" if the Earth moves, and would never fall in the same place, Copernicus argued that this will not occur as all objects in the Earth's vicinity participate in its motion and are being carried by it.

Copernicus was aware that these ideas would inevitably create conflicts with the Church, and they did. Though he informally discussed his ideas he waited until he was about to die to publish his magnum opus, of which he only printed a few hundred copies. Nonetheless this work was far from ignored and in fact was the first (and perhaps the strongest) blow to the Medieval cosmology. His caution did not save him from pointed criticisms, for example, Luther pointed out (from his *Tabletalk*)

> *There was mention of a certain new astrologer who wanted to prove that the Earth moves and not the sky, the Sun, and the Moon. This would be as if somebody were riding on a cart or in a ship and imagined that he was standing still while the Earth and the trees were moving* [2]*. So it goes now. Whoever wants to*

[2]This was a prescient remark, see Sect. ?? and Chap. 6.

> *be clever must agree with nothing that others esteem. He must do something of his own. This is what that fellow does who wishes to turn the whole astronomy upside down. Even in these things that are thrown into disorder I believe the Holy Scriptures, for Joshua commanded the Sun to stand still and not the Earth.* [3]

The Pope Paul III was not very critical, but his bishops and cardinals agreed with Luther and the model was condemned by the Church.

The heliocentric model was eventually universally accepted by the scientific community, but it spread quite slowly. There were several reasons for this, on the one hand there certainly was a reticence to oppose the authority of the Church and of Aristotle, but there was also the fact that the heliocentric model apparently contradicted the evidence of the senses. Nonetheless the model became better known and was even improved. For example, Copernicus' version had the fixed stars attached to an immovable sphere surrounding the Sun, but its generalizations did and assumed them to be dispersed throughout the universe (Fig. 3.4); Giordano Bruno even proposed that the universe is infinite containing many worlds like ours where intelligent beings live.

In fact it was Bruno's advocacy of the Copernican system that produced one of the strongest reactions by the Church: Bruno advocated not only the heliocentric model, but denied that objects posses a natural motion, denied the existence of a center of the universe, denying even the Sun of a privileged place in the cosmos. Bruno was executed by the Inquisition in 1600.

[3]This statement was produced during an informal after-dinner conversation and was published after Luther's death; it should therefore be taken with caution.

Giordano Bruno (1548–1600). Born in Nola, near Naples. He became a Dominican monk and learned Aristotelian philosophy and he was attracted to “unorthodox” streams of thought (eg. Plato). Left Naples (1576) and later Rome (1577) to escape the Inquisition. Lived in France until 1583 and in London until 1585. In 1584 he published *Cena de le Ceneri* (The Ash Wednesday Supper) and *De l'Infinito, Universo e Mondi* (On the Infinite Universe and Worlds). In the first he defended the heliocentric theory (though he was clearly confused on several points); in the second he argued that the universe was infinite, containing an infinite number of worlds inhabited by intelligent beings. Wherever he went, Bruno's passionate utterings led to opposition; he lived off the munificence of patrons, whom he finally outraged. In 1591 he moved to Venice where he was arrested by the Inquisition and tried; he recanted but was sent to Rome for another trial, he did not recant a second time. He was kept imprisoned and repeatedly interrogated until 1600 when he was declared a heretic and burned at the stake. It is often maintained that Bruno was executed because of his Copernicanism and his belief in the infinity of inhabited worlds. In fact, we do not know the exact grounds on which he was declared a heretic because his file is missing from the records. Scientists such as Galileo and Johannes Kepler were not sympathetic to Bruno in their writings.

The slow progress of the heliocentric model was also apparent among part of the scientific community of the time; in particular Tycho Brahe, the best astronomer of the late 16th century, was opposed to it. He proposed instead a “compromise”: the earth moves around the sun, but the rest of the planets move around the Earth (Fig. 3.5). Brahe's argument against the Copernican system was roughly the following: if the Earth moves in circles around the Sun, nearby stars will appear in different positions at different times of the year. Since the stars are fixed they must be very far away but then they should be enormous and this is “unreasonable” (of course they only need to be enormously bright!)

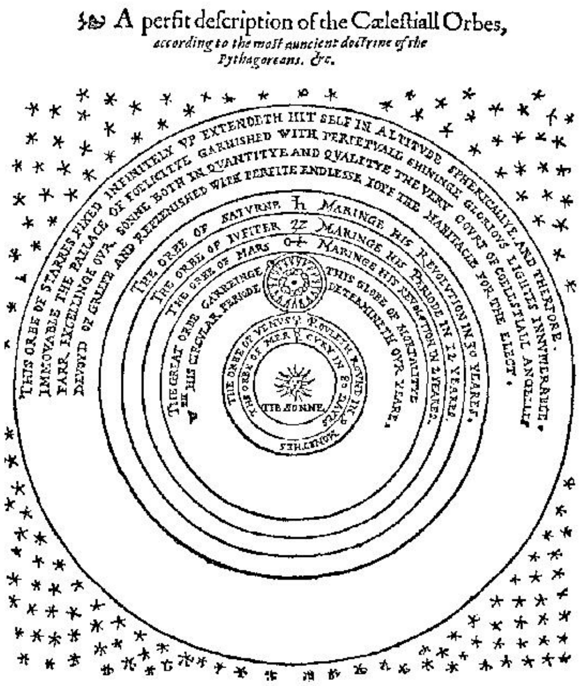


Figure 3.4: The heliocentric model of Thomas Digges (1546-1595) who enlarged the Copernican system by asserting that the stars are not fixed in a celestial orb, but dispersed throughout the universe.

Tycho Brahe (14 Dec 1546 - 24 Oct 1601). Born in Denmark he was fascinated by astronomy and, being a wealthy man (and being helped by the Danish monarchy), was able to devote a lot of time to the meticulous recording of the observed trajectories of the planets. He rented the island of Hven from the king of Denmark and set up a state of the art observatory there (without telescopes, they did not appear for 100 years). He later had to leave this island having has a disagreement with the king over religious matters. He then went to Prague as Imperial Mathematician and it was there that he interacted with Kepler. He did not adopt the Copernican system

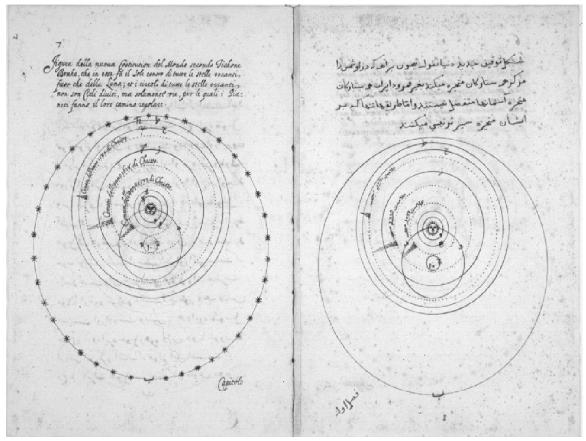


Figure 3.5: Brahe's model of the universe: a central Earth around which the sun moves surrounded by the other planets [From the *Compendio di un trattato del Padre Christoforo Borro Giesuita della nuova costitution del mondo secondo Tichone Brahe e gli altri astologi moderni* (Compendium of a treatise of Father Christoforo Borri, S.J. on the new model of the universe according to Tycho Brahe and the other modern astronomers) by Pietro della Valle, Risalah- i Padri Khristafarus Burris Isavi dar tufiq-i jadid dunya.

3.3.1 Aristotle in the 16th century

In 1572 Tycho observed a star which suddenly appeared in the heavens (we now recognize this as an exploding star: a supernova). He noted that this "new star" did not change in position with respect to the other stars and should therefore be in the outer sphere of Aristotle's universe. But this was supposed to be an eternal, unchanging sphere! He published these observations in *The Nova Stella* in 1574. The same type of problems arose due to his observations of a comet which appeared in 1577, for he could determine that this object was farther than Venus again contradicting the Aristotelian idea that the universe beyond the Moon was perfect, eternal and unchanging. This is a case where better observations when pitted against the best theory of the time produced discrepancies which, in time, proved to be fatal to the current model and would eventually give rise to a better, more precise theory of the universe (see Sect. **??**).

By this time also most of the Medieval approach to physics had been shed, though not completely. For example, the motion of a projectile was thought to be composed of an initial violent part (when thrown) and a subsequent natural part (which returns it to the ground). Still it was during

this time that the importance of velocity and force in determining the motion of objects was realized.

The birth of new theories is not easy, however. In this case it was not until the late 17th century that a complete new view of the universe was polished and could be used as a tool for investigating Nature. By this time the Aristotelian doctrine was, finally, set aside. The first step in this long road was taken by Copernicus, the next by Johaness Kepler in his investigations of the motion of the planets and then by Galielo through his investigations on the nature of motion and his description of the solar system.

3.4 Kepler

Johaness Kepler readily accepted the Copernican model, but his first attempts to understand the motion of the planets were still tied to the Aristotelian idea that planets “must” move on spheres. Thus his first model of the solar system was based on the following reasoning: there are, he argued, six planets (Uranus, Neptune and Pluto would not be discovered for almost 300 years) which move on the surfaces of spheres. There are also five perfect geometric figures, the Platonic solids: cube, tetrahedron, octahedron, icosahedron and dodecahedron. Then, he argued that the relative sizes of the spheres on which planets move can be obtained as follows (see Fig. 3.6)

- Take the Earth’s sphere and put a dodecahedron around it.
- Put a sphere around this dodecahedron, Mars will move on it.
- Put a tetrahedron around Mars’ sphere and surround it by a sphere, Jupiter will move on it.
- Put a cube around Jupiter’s sphere and surround it by a sphere, Saturn will move on it.
- Put an icosahedron inside the Earth’s sphere, then Venus will move on a sphere contained in it.
- Put a octahedron inside Venus sphere, then Mercury will move on a sphere just contained in it.

Therefore the ordering is octahedron, icosahedron, dodecahedron, tetrahedron, cube (8-faces, 20-faces, 12-faces, 4-faces, 6-faces). He spent 20 years trying to make this model work...and failed: the data would just not agree

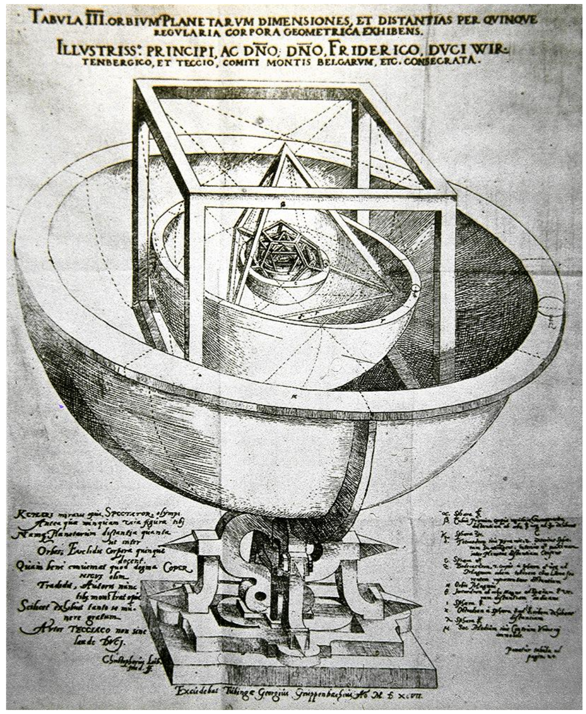


Figure 3.6: Illustration of Kepler's geometrical model of the solar system

with the model. Hard as this was, he dropped this line of investigation. This work, however, was of some use: he was recognized as "someone" and, in 1600, was hired by Tycho Brahe (then in Prague) as an assistant (at miserly wages). Tycho was very reluctant to share his data with Kepler (who was also made fun for being provincial); Tycho died in 1601 and the king appointed Kepler as successor (at a much smaller salary which was irregularly paid).

For many years thereafter Kepler studied Tycho's data using the heliocentric model as a hypothesis. In 1609 he determined that Mars does not move in a circle but in an ellipse with the sun in one of the foci and that in so moving it sweeps equal areas in equal times. This later blossomed into his first and second laws of planetary motion. Ten years after he discovered his third law: the cube of the average distance of a planet to the sun is proportional to the square of its period. All this was very important: Tycho's data, thanks to Kepler's persistence and genius, finally disproved the epicyclic theory and, on top of this, the idea that planets must move in circles.

This is a good example of the evolution of a scientific theory (see Sect. ??). The data required Kepler to modify the original hypothesis (planets move in circles with the sun at the center) to a new hypothesis (planets move in ellipses with a sun at one focus). He showed that this was the case for Mars, and then checked whether it was also true for the other planets (it was).

Johannes Kepler. (Dec 27 1571 - Nov 15 1630). Born Weil der Stadt, Germany. Died Regensburg, Germany. Educated in Tübingen where he became acquainted with the Copernican system, which he embraced and sought to perfect; in 1596 he published *Mysterium Cosmographicum* in which he defended the Copernican theory and described his ideas on the structure of the planetary system. He was a devout Lutheran but inclined towards Pythagorean mysticism. He was intoxicated by numbers and searched for simple mathematical harmonies in the physical world; in particular he believed that the planets emit music as they travel and he even gave the various tunes. In 1609 he published *Astronomia Nova* ("New Astronomy") which contained his first two laws. In 1619 he published *Harmonices Mundi* (Harmonies of the World) in which he stated his third law.

The three laws obtained by Kepler are

1. Planets move in ellipses with the sun at one focus; see Fig. 3.7.
2. Planets sweep equal areas in equal times in their motion around the sun; see Fig. 3.8.
3. The average distance to the sun cubed is proportional to the period squared; see Table 3.1 for the data which led Kepler to this conclusion.

Kepler's 1st law: Planets move in ellipses with the sun at one focus

Kepler's 2nd law: Planets sweep equal areas in equal times in their motion around the sun

Kepler's 3rd law: The average distance to the sun cubed is proportional to the period squared

The first two laws describe the motion of single planets, the third law relates the properties of the orbits of different planets.

Kepler did not know why planets behaved in this way. It was only about 50 years later that Newton explained these laws in terms of his universal law of gravitation. In modern language these results imply the following (discovered by Newton): the planets move the way they do because they experience a force from the sun, this force is directed along the line from the planet to the sun, it is attractive and decreases as the square of the distance.

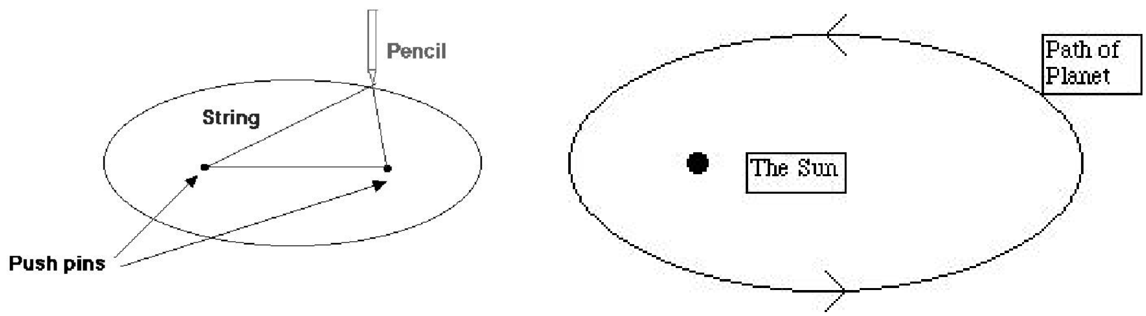


Figure 3.7: How to draw and ellipse (left) and the elliptical orbit of planets (right)

Planet	Period (years)	Avg. dist. (AU)	Period ^{2}	Dist^3
Mercury	0.24	0.39	0.06	0.06
Venus	0.62	0.72	0.39	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51
Jupiter	11.9	5.20	142	141
Saturn	29.5	9.54	870	868

Table 3.1: Period and average distancs for the innermost five planets, a plot of the last two columns gives a straight line as claimed by Kepler's third law.

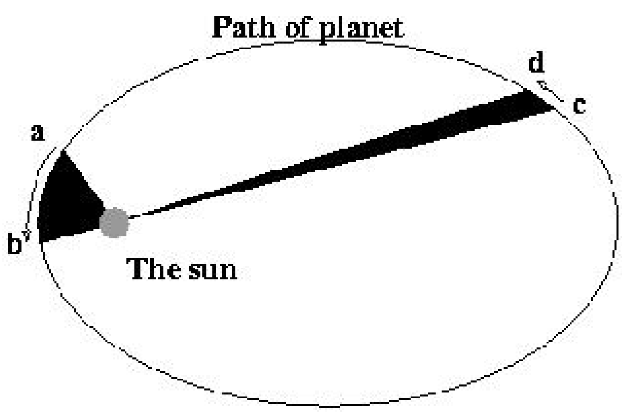


Figure 3.8: The planet in a given time moves from **a** to **b** sometime later it reaches **c** and it takes the *same* time to go from **c** to **d**. Kepler's second law states that the shaded areas are equal